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RESEARCH MEMORANDUM

ADDITIONAL EXPERIMENTAL HEAT-TRANSFER AND DURABILITY

DATA ON SEVERAL FORCED-CONVECTION, AIR-COOLED,

STRUT-SUPPORTED TURBINE BLADES OF

IMPROVED DESIGN

By Eugene F. Schum

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RESEARCH MEMORANDUM

ADDITIONAL EXPERIMENTAL HEAT-TRANSFER AND DURABILITY DATA ON

SEVERAL FORCED-CONVECTION, AIR-COOLED, STRUT-SUPPORTED

TURBINE BLADES OF IMPROVED DESIGN

By Eugene F. Schum

SUMMARY

An investigation has been underway at the NACA Lewis laboratory to develop air-cooled, strut-supported turbine blades. As part of this program six blades were investigated in a full-scale turbojet engine to obtain data on blade durability and to obtain the blade-cooling effectiveness and strut temperature trends at turbine-inlet gas temperatures higher than had been previously reported. These blades consisted of a machined, finned internal load-carrying member, or strut, to which a two-piece cast base and a two-piece airfoil shell were attached by brazing. The strut and blade base were fabricated from Timken 17-22A(S) steel and the shell, from N-155 material.

At the higher turbine-inlet gas temperature of 1815° F and at engine speeds to 11,500 rpm, the measured strut temperatures were as expected on the basis of analytical methods. At this gas temperature, the measured temperature differences between the midchord and the leading-edge regions and between the midchord and the trailing-edge regions of the strut were of the order of 20° and 175° F, respectively. These differences were comparable with the difference measured at a lower turbine-inlet temperature of 1650° F. Substantial differences were obtained between the effective gas and strut temperatures. At a coolant-flow ratio of 0.012 and a turbine-inlet temperature of 1815° F, for example, the average strut temperature at the 3/8 span location was 1025° F, approximately 575° F below the effective gas temperature. Calculated spanwise blade temperatures for this gas temperature verified the need of a protective coating on the steel strut to prevent oxidation. Oxidation problems of the N-155 shell were not expected. Calculated strut temperatures were generally 20° F below experimental values.

In a steady-speed durability investigation, conducted at a rated engine speed of 11,500 rpm and a turbine-inlet gas temperature of 1670° F, the four blades tested failed earlier than expected from stress-rupture considerations. Failures occurred from fatigue at the base

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region of the strut where the calculated centrifugal stress was 44,000 pounds per square inch. Elimination of the fatigue failures to obtain greater blade life will probably require a different fabrication technique and a more suitable heat treatment to provide sufficient ductility. Even with these fatigue failures, however, the blade life of the four strut blades operated at constant engine speed gave indication that strut blade life for the coolant-flow ratios investigated will probably be greater than that for a tube-filled, shell-supported blade made from the same material.

Two of the six blades were subjected to a cyclic-speed endurance investigation in order to ascertain the severity of blade thermal stresses caused by rapidly changing gas temperatures. In addition to the successful completion of 10 cycles at coolant-flow ratios of 0.05 and 0.03 reported earlier, both blades successfully completed 10 additional cycles at a ratio of 0.02. One of the two blades completed 14 cycles at 0.01. Both blades failed from fatigue at the base region of the strut. These cyclic endurance results were encouraging even though the average life of each blade, which was approximately 40 cycles, was less than a goal of 200 cycles.

INTRODUCTION

One of the goals of turbine-cooling research is to obtain forced-convection, air-cooled turbine-blade configurations that will operate satisfactorily at elevated turbine-inlet gas temperatures with a small amount of cooling air. Strut-supported blades have shown promise of operation at low coolant-flow ratios (coolant-to-gas-flow ratio) at elevated turbine-inlet temperature levels (refs. 1 to 4). Consequently, research is being directed to the study of cooling effectiveness and durability of this type of blade.

The principle of the strut-supported blade is that the main load of the blade is carried by an internal finned strut. The strut is surrounded by cooling air and is protected from the hot combustion gases by means of an airfoil-shaped shell. The shell is attached to and supported by load-carrying fins on the strut. Because the shell is not a principal load-carrying member of the blade, it is permitted to operate at a relatively higher temperature than that of the strut.

As a result of the analysis in reference 1 and an investigation of the first NACA strut blade in reference 2, a more detailed analysis of the strut-type blade was made in reference 3. This analysis considered in detail the various factors affecting the cooling characteristics and design criteria of strut blades. A second strut blade design was evolved in which the support member of the blade was of nonstrategic material (Timken 17-22A(S) steel). The cooling effectiveness of this blade was experimentally evaluated in reference 3 at only one turbine-inlet gas

temperature, 1650° F, and one engine speed, 11,500 rpm. A limited amount of blade durability obtained during cyclic engine operation is also included. This improved or second strut blade design of reference 3 varied from that of reference 2 in the following respects: (1) the design was for a higher gas temperature (2000° F) and a higher cooling-air inlet temperature (450° F), (2) the aerodynamic shape was thinner and the profile twisted from root to tip, and (3) provision was made for a more uniform distribution of the cooling air in the blade base.

As a continuation of the work of reference 3, an experimental investigation of the improved or second blade design was made in order to obtain more information on blade durability and to extend the range of data on the blade heat-transfer characteristics to a turbine-inlet temperature of 1815° F.

The purposes of the durability investigation conducted herein were (1) to obtain durability data on four blades operated at constant engine speed, (2) to obtain durability data on two blades subjected to cyclic engine speeds, and (3) to evaluate the possible causes of blade failures, if they occurred, in an effort to determine means of eliminating the failures. Cyclic-type operation was used to determine to some extent the severity of blade thermal stresses caused by the rapidly changing gas temperatures for comparison with operation at steady engine speeds.

The purposes of the heat-transfer investigation were (1) to ascertain whether blade oxidation problems will be encountered at turbine-inlet gas temperatures of the order of 1815° F, (2) to present additional heat-transfer data, covering a wide range of engine operating conditions, and (3) to determine whether blade operation at a turbine-inlet temperature of 1815° F will result in severe chordwise temperature gradients in the strut. At present, chordwise gradients must be experimentally obtained since analytical techniques for calculating these gradients have not been developed.

Favorable agreement of calculated and measured strut temperatures in the midchord region would be expected for an inlet-gas temperature of 1815° F as was obtained in reference 3 for a lower inlet-gas temperature of 1650° F. An increase of 165° F in gas temperature should not have a large effect on the heat-transfer factors used in the calculation of the strut temperatures.

The data of the strut blade-cooling effectiveness were obtained in a full-scale, modified turbojet engine for a range of engine speeds from 4000 (idling engine speed) to 11,500 rpm (rated engine speed), which correspond to turbine tip speeds of 450 and 1300 feet per second, respectively. The turbine-inlet gas temperature ranged from 1050° to 1815° F. During these tests, the coolant-flow ratio per blade was varied from 0.009 to 0.09 and the blade-inlet coolant temperature ranged from 120° to 280° F.

The steady-speed endurance investigation was conducted at the rated speed of 11,500 rpm (calculated centrifugal stress of 44,000 psi at base of strut) and at turbine-inlet temperature of 1670° F. The cyclic type of endurance operation consisted of a rapid acceleration from engine idle speed to rated speed. Rated engine speed was maintained for 15 minutes and was followed by a rapid deceleration to idle speed.

APPARATUS

In this investigation, the cooling effectiveness and blade durability were determined from full-scale engine tests. Since the blades investigated are identical in configuration to those of reference 3, only a brief description of the blade along with the test engine is included herein. A detailed description of the blade design and fabrication technique can be found in reference 3.

Blades

The twisted airfoil-shaped blades used in this investigation were constructed of five pieces - a strut, a split (two-piece) base, and a two-piece shell - which were brazed into an integral structure. An isometric view of the component parts is shown in figure 1. Cross sections of the strut configuration at three spanwise locations, blade root, 3/8 span, and 7/8 span (0, $1\frac{1}{2}$, and $3\frac{1}{2}$ in. from the blade base platform, respectively), and pertinent configuration dimensions are shown in figure 2.

The strut and blade bases were fabricated from Timken 17-22A(S) material, an alloy containing only 3 percent critical material. The thin airfoil shell (0.020 in. thickness) was formed from N-155 material, an alloy containing high percentages of nickel, chromium, and other critical metals. This material was required in order to provide sufficient shell strength for elevated operating temperatures and to withstand the corrosive action of the hot combustion gases without the use of protective coatings. The blade chord and blade span were approximately 2 and 4 inches, respectively. The weight of this blade is equivalent to that for shell-supported blades (of the same general blade size) and approximately two-thirds that of the standard, uncooled blades of the test engine.

Because of inexperience in brazing strut-supported blades at the start of this investigation, numerous brazing cycles were required in the fabrication process. One cycle was required to braze the strut into the split base, while a second cycle was used to braze the shell to the strut. In many instances, rebrazes or additional cycles were found necessary when the quality of previous brazes was questionable. Because it was thought that numerous brazing cycles were undesirable with respect to

blade strength, the fabrication process was altered during the durability investigation and will be discussed later. The various heat treatments employed in the fabrication of the strut blades for the blade durability tests will also be discussed in more detail in a subsequent section.

Engine

The strut blades used in the heat-transfer and blade-durability phases of the investigation were tested in a modified, full-scale turbojet engine, the detailed description of which is given in reference 5. The engine modification permitted the substitution of one to four air-cooled turbine blades in place of the uncooled standard blades of the test engine. Cooling air was supplied to the blades from an external source through a tail cone modified to include a cooling-air ducting system. The engine was equipped with an adjustable tail-pipe nozzle so that the turbine-inlet temperature could be varied through a range at a given engine speed.

Instrumentation

Blades. - Chromel-alumel thermocouples and a thermocouple system similar to that described in reference 5 were used in this investigation. Three thermocouples were located on the air-cooled blades at the $3/8$ span position and were embeded in the strut near the leading-edge, midchord, and trailing-edge regions as shown in figure 2. The $3/8$ -span location was selected for thermocouple instrumentation because calculations indicated that this was the critical span location with respect to stress and temperature. The cooling-air temperature at the entrance to the blade base was measured by a thermocouple that was inserted in a cooling-air supply tube on the rotor face, a set-up similar to that described in reference 5.

Engine. - The general instrumentation of the engine, including the measurement of combustion gas flow, effective gas temperature, and so forth, was similar to that described in reference 5.

PROCEDURE

Experimental Procedure

Heat-transfer investigation. - The cooling effectiveness of the strut blade was obtained from an experimental heat-transfer investigation made in the full-scale turbojet engine and conducted in a manner similar to that described in reference 5. Experimental data were obtained on two strut blades over a range of engine speeds from 4000 (idling speed) to 11,500 rpm (rated speed) and over a range of turbine-inlet temperatures

from 1050° to 1815° F. At each engine speed the cooling air was varied over a range of coolant-flow ratios from approximately 0.009 to 0.09 per blade. The resulting coolant temperature ranged from 120° to 280° F. These values of coolant-flow ratio were dependent upon a calibration of coolant leakage between the rotating and stationary parts of the cooling-air system. The calibration is described in reference 6.

Blade-durability investigation. - The durability of six strut blades was determined by two experimental methods of turbojet-engine endurance testing; namely, steady-speed and cyclic-speed engine operation.

The steady-speed endurance testing was conducted at the rated engine conditions of 11,500 rpm and a turbine-inlet gas temperature of 1670° F. Four of the six blades were subjected to this type of endurance test.

Each blade was tested separately and investigated at a predetermined coolant-flow ratio to determine the blade life for that flow ratio. The coolant-flow rate was adjusted to the desired value once the engine speed and the gas temperature were established. Blade endurance was investigated at coolant-flow ratios of 0.01, 0.015, and 0.018.

In the cyclic phase of the investigation, each cycle consisted of engine operation at idle conditions for 5 minutes (4000 rpm and a turbine-inlet gas temperature of 1070° F), acceleration to rated engine conditions in 15 seconds (11,500 rpm and a turbine-inlet temperature of 1670° F), 15 minutes at rated conditions, and then followed by a deceleration to idle conditions in 15 seconds. At the rated engine conditions, the temperature of the uncooled standard engine blades (used as the effective gas temperature herein) was 1450° F.

Calculation Procedure

Experimental average strut temperatures. - The average strut temperature reported herein is the arithmetic average of the leading-edge, midchord, and trailing-edges sections of the strut at the 3/8-span position (fig. 2(b)).

Calculated strut and shell temperatures. - The calculated temperatures of the strut and shell of the strut-supported blade were determined with the use of the electric analog described in reference 4. The method for obtaining the temperatures is comprehensively described in references 3 and 4. Blade temperatures were calculated for strut blade locations a, g, o, and s shown in figure 2(b) (which correspond to locations a, g, o, and s of figs. 9(b) and (c) of ref. 4). Points a and g are shell locations while points o and s are strut locations. Temperatures were also calculated at corresponding positions along the blade span at 1/2-inch intervals in order to gain knowledge of the spanwise temperatures and to

provide a comparison with experimentally measured temperatures obtained at points at 3/8-span location of the blade. Temperatures for the mid-chord region of the blade were the only temperatures calculated because the theory used is applicable only to this region as cited in reference 4.

RESULTS AND DISCUSSION

The results of the investigation of the strut-supported blades during engine operation are included in the following sections entitled Heat-Transfer Investigation and Blade-Durability Investigation.

Heat-Transfer Investigation

The heat-transfer investigation was conducted to extend the results of reference 3 from a turbine-inlet gas temperature of 1650° to 1815° F, an increase of 165° F. With this increase of only 165° F, it was expected that the experimental midchord strut temperature would compare favorably with the analytical predictions. It would be worthwhile, however, to determine whether blade operation at the elevated gas temperature would result in excessive chordwise temperature gradients between the strut midchord and the leading- or trailing-edge regions of the strut. At present, such gradients must be obtained by experimental measurements since analytical methods have not been developed. The experimentally obtained strut temperatures and a comparison of the midchord temperatures with calculated values are presented. Spanwise strut and shell temperatures are also shown in order to indicate the problems associated with oxidation and braze strength for extended blade operation.

Experimental blade-temperature distribution. - Strut temperature variations measured at the leading-edge, midchord, and trailing-edge regions of the strut are shown in figure 3. The data presented were obtained at the 3/8 span position for a range of coolant-flow ratios and for two nominal turbine-inlet gas temperatures of 1650° and 1815° F (corresponding nominal effective gas temperatures of 1425° and 1590° F, respectively). Engine speed for these data was 11,500 rpm, which is equivalent to a turbine tip speed of 1300 feet per second. The variation of the coolant temperature measured at the blade base is also shown. The data shown for the lower gas temperature are the same as those shown in figure 6 of reference 3, but are included herein for comparison with the data obtained at the higher gas temperature.

For both gas temperatures, the strut data indicate that there is a relatively small temperature difference between the leading-edge and midchord regions of the strut, the difference being of the order of 20° F. A larger temperature difference of approximately 175° F occurs between the trailing-edge and midchord regions of the strut, the difference being

primarily attributed to space limitations in the trailing-edge region. As can be seen in figure 2, the primary and secondary fins in this region are of relatively short length which tends to reduce the cooling effectiveness of the strut and thereby to increase strut temperatures.

A substantial difference between the strut temperature and the effective gas temperature was obtained for this blade over the range of coolant-flow ratios investigated. For example, at a coolant-flow ratio of 0.01 and an effective gas temperature of 1400°F , this difference is approximately 400°F . For the higher effective gas temperature of 1590°F and a comparable coolant-flow ratio of 0.012, this difference is of the order of 575°F , a sizable temperature difference for a coolant-flow ratio of such small magnitude. The data used for these curves as well as strut-temperature data for other engine operating conditions are shown in table I. Data are not presented for strut-temperature measurements at other spanwise locations because of thermocouple failures early in the investigation.

An indication of the chordwise strut-temperature distribution near the blade base may be obtained from a photograph of a blade shown in figure 4; the blade shell was removed after operation at an engine speed of 11,500 rpm and a turbine-inlet temperature of 1650°F . The heavy lines on the strut are bands of temper color. (A temper color band on a metal surface is a colored area or line caused by oxide formation at a specific temperature.) For a given material, say the strut material, the color of the lines is dependent upon the imposed strut temperature that occurs during engine operation. A photograph of a blade in which only the lines of a given color were shown would indicate the isothermal lines. Line X of figure 4 is a typical isothermal line resulting from engine operation at a given value of coolant-flow ratio. For a larger coolant-flow ratio, greater cooling of the strut is obtained and the isothermal line occurs at a greater radial location, as line Y indicates. The temperature indicated by line X is identical to that indicated by line Y. It is therefore apparent that each separate line along the blade span is a temper line for a different coolant-flow ratio. These separate lines of constant temperature that occur along the blade span are relatively flat in the midchord region, thus indicating that there is a small temperature gradient at this location. This verifies the basic assumption made in reference 4 for the calculation of strut blade temperatures.

Comparison of calculated and experimental midchord strut temperatures. - A comparison of calculated and experimentally obtained midchord strut temperatures at the blade 3/8-span location is shown in figure 5. The calculated and experimental midchord strut temperatures and calculated midchord shell temperatures are presented for two nominal turbine-inlet gas temperatures of 1650°F and 1815°F (corresponding to nominal effective gas temperatures of 1425°F and 1590°F , respectively) for a range of coolant-flow ratios. The calculated and experimental strut

temperatures for the lower gas temperature (fig. 5(a)) are identical to those of figure 8 of reference 3. The calculated shell temperatures are, however, for location a (see fig. 2(b)) and not the same as the average shell temperatures shown in reference 3.

For both values of turbine-inlet gas temperature, favorable agreement was obtained between the calculated and experimental midchord strut temperatures, the difference being of the order of 20° F. With an increase of gas temperature from 1650° to 1815° F, a large change in the factors affecting heat-transfer (such as gas-to-blade heat-transfer coefficient) was not expected. The favorable agreement shown in figure 5(b), however, does provide additional verification of the method of calculating blade temperatures for strut-supported blades.

Knowledge of the shell temperatures is also required for strut-supported blade designs. Possible oxidation problems and temperature and shear stress limitations imposed by the braze between the shell and the strut at elevated operating temperatures must be considered. For both values of turbine-inlet gas temperature, the calculated midchord shell temperatures for low coolant-flow ratios were of the order of 275° F lower than the effective gas temperature. At larger coolant-flow rates this difference is approximately 575° F. Experimental values of shell temperatures, for comparison with calculated values, are not shown. The thickness of the shell (0.020 in.) precluded measurements of shell temperatures by means of thermocouples because at the present time, rotating thermocouple instrumentation of sufficient accuracy and durability for such thin shells has not yet been fully developed. Nevertheless, the calculated shell temperatures should be expected to be representative of actual operating temperatures because of the favorable agreement achieved between calculated and experimental midchord strut temperatures. It is interesting to note that for rated engine conditions and a coolant-flow ratio of 0.03, the calculated midchord shell temperature of the strut blade is approximately 200° and 300° F higher than measured midchord shell temperatures of a tube-filled, shell-supported blade and a corrugated insert, shell-supported blade, respectively (ref. 7). A higher strut blade shell temperature is typical for strut-type blades. Even with the higher shell temperature shown, the strut or support member of the strut blade in the midchord region is approximately 275° and 175° F lower than the midchord shell temperature (or temperature of the primary support member) of the tube-filled and corrugated-insert blades, respectively.

Calculated spanwise temperature distribution for strut blade. - In the design of strut-supported blades, knowledge of the spanwise temperature distribution of the strut and shell is usually required. Calculated spanwise strut temperatures and centrifugal stresses that would be expected during engine operation are used in conjunction with the strength characteristics of the strut material to obtain adequate proportioning of

the strut in order to provide sufficient blade life. Strut and shell temperatures along the blade span are needed to establish whether oxidation problems will be encountered, and whether the brazed joint between the shell and the strut at various span locations will safely withstand the imposed centrifugal load caused by the shell.

Figure 6 shows the results of such calculations for the strut configuration investigated. The results presented are for a turbine-inlet gas temperature of 1815°F (effective gas temperature of 1590°F), rated engine speed of 11,500 rpm (tip speed of 1300 ft/sec), and two coolant-flow ratios of 0.012 and 0.084. The calculated blade and coolant temperatures are for the effective gas temperature distribution shown. The effective gas temperature distribution is typical for the turbojet engine used in this investigation and was extrapolated for higher gas temperatures from unpublished experimental results. The experimental midchord strut temperature and the effective gas temperature at $3/8$ span is also shown. Over the length of the strut (3.55 in.) there is a steady increase of strut temperature of the order of 350°F for the lower coolant-flow rate, while the increase in coolant temperature is approximately 550°F . For the larger coolant-flow rate, the temperature rises are considerably less, being of the order of 200°F for the strut and approximately 225°F for the cooling air. For both coolant-flow rates the largest temperature gradient in the blade occurs between points a and g of the shell. For continued engine operation at the conditions shown in figure 6(a), it appears from the shell temperature distribution that serious oxidation of the shell material used would not be expected. On the otherhand, however, the calculated strut temperatures along the blade span verified the need for the nickel-plate coating (ref. 3) of the steel strut which was used in the fabrication of this blade. Whether a strut has proper proportioning and whether the brazed media have sufficient strength to provide suitable blade life can be determined only from an extensive endurance investigation of the blade at the engine conditions being considered. Endurance tests were not conducted in this investigation at the 1815°F turbine-inlet gas temperature because the standard, uncooled blades of the test engine would be incapable of sustained operation at this temperature.

Blade-Durability Investigation

A total of six strut blades was used in the cyclic-speed and steady-speed phases of the blade-durability investigation. Strut blades 1 to 4 were subjected to steady-speed endurance tests at rated engine conditions of 11,500 rpm (turbine tip speed of 1300 ft/sec) and a turbine-inlet gas temperature of 1670°F . Blades 5 and 6 were subjected to the cyclic-speed endurance tests, which consisted of a rapid acceleration from idle engine conditions to rated engine conditions followed after 15 minutes by a rapid deceleration to the idle engine conditions. A detailed discussion of the durability of each blade and a summary of the durability

investigation including pertinent strut blade design information are included herein. The various heat treatments used during the course of the durability investigation are given in table II.

Strut blade 1. - This blade was given heat treatment A (table II) which consisted of a 1-hour normalizing at 1725° F and a 4-hour temper at 1225° F. During both these furnace treatments, the blade was protected from oxidation by immersion in an argon atmosphere. This heat treatment was selected because of the resulting high stress-to-rupture strength that is obtainable. After 2 hours and 29 minutes operation at a low coolant-flow ratio of 0.01, a failure occurred in the strut at the junction of the strut and the blade base. A photograph of the blade after the failure is shown in figure 7. Examination of the blade base to ascertain the cause of the failure indicated a fatigue-type fracture, as evidenced by the light, semicircular areas of the strut shown in figure 7(b). It was observed that the fatigue cracks originated on the suction surface of the blade and progressed toward the center of the strut until a tensile failure caused a complete strut rupture. A metallurgical examination of the blade after failure indicated that the cracks originated at approximately the same time, which shows that the stresses in the strut are fairly uniformly distributed. The calculated centrifugal stress imposed on the strut at this blade location was 44,000 pounds per square inch. The nature of the failure denoted that the strut material did not have sufficient ductility to withstand the combination of the imposed vibratory stresses, centrifugal stresses, and stress concentrations caused by the notches in the fillet region of the blade.

Strut blade 2. - The knowledge gained from the experimental results of blade 1 was then employed in the fabrication of blade 2. This blade was given heat treatment B, a treatment similar to A (blade 1) but with a tempering temperature 125° F higher (1350° F). A higher tempering temperature was used in order to increase the ductility of the strut material in an attempt to eliminate possible fatigue failures. The coolant-flow ratio used for the endurance evaluation of this blade was increased to 0.015. After approximately 10 hours of operation at this coolant-flow rate, an inspection of the blade revealed cracks in the thin shell material in the fillet region of the blade on the suction as well as the pressure side of the blade. Operation of the blade with these cracks was continued, however. Cracks in the shell are not expected to seriously affect the strength since the strut, and not the shell, is the primary support member. After 30 hours and 50 minutes of engine operation a fatigue-type failure, similar to that of blade 1, occurred in the base region of the strut. Although the blade life was greater than that for blade 1, it was less than expected from stress-to-rupture considerations. The increase in tempering temperature did not eliminate the fatigue problem.

It was now felt that the number of brazing cycles used in the blade fabrication process of blades 1 and 2 might have a more detrimental effect

on blade life than was thought earlier. Blades 1 and 2 were subjected to four and three brazing cycles, respectively, because of the fabrication problems discussed earlier in the description of the blades. The corrosive action of the braze on the strut fins in the fillet region of a strut blade which has been subjected to several braze cycles is shown in figure 8. The figure indicates where the thickness of the fins has been reduced by the corrosive action of the braze. Successive cycles also increased braze diffusion into the strut material, causing a brittle and notch-sensitive material.

The extent of braze penetration into a typical 0.020-inch secondary fin of strut blade 2 determined from a microscopic examination of a square section of the blade removed after failure is shown in figure 9. The enlarged view is a section where the secondary fin is brazed into the blade base. The normal grain structure of the 17-22A(S) material and the braze-affected grain structure of the secondary fin can be readily seen. Complete intergranular diffusion of the braze material through the fin shown in figure 9 was observed in many other secondary and primary fins (0.040 in. thickness). It is believed that the large grain size in conjunction with braze diffusion is conducive to fatigue-type failures (ref. 6). Severe undercutting of the fin by the braze material also occurred (see fig. 9). Similar undercutting and diffusion was also evidenced in a durability investigation of a tube-filled, shell-supported blade (ref. 6).

Strut blade 3. - In an effort to reduce possible braze penetration, strut blade 3 was brazed in only one cycle by altering the blade fabrication technique. The blade was given heat treatment A and operated at a coolant-flow ratio of 0.01; the heat treatment and coolant-flow rate being similar to that for blade 1. After 3 hours and 5 minutes, the now familiar fatigue-type failure occurred in the base fillet region of the strut, a failure similar to that shown in figure 7. Although it is thought that repeated braze cycles have a detrimental effect on blade life, this did not seem to be the only cause of failure, because the life of blade 3 was only a little longer than that of blade 1.

Strut blade 4. - The fact that blade 3 failed in fatigue after the use of only one braze cycle indicated that an even greater amount of strut ductility was needed in conjunction with the use of one braze cycle. Strut blade 4 was therefore assembled in one brazing operation and given heat treatment C, a treatment slightly different from A. The base of the blade and a portion of the strut extending from the base to 3/4 inch measured from the top of the blade platform was submerged for 1 hour in a salt bath at 1375° F. The salt bath provided a tempering temperature 150° F higher than that of blade 3. This type of dual tempering treatment of the blade base section was demonstrated in reference 6 to greatly improve the blade life of air-cooled, shell-supported blades. The improvement in strut blade life was not so apparent, however, because after

only 14 hours and 25 minutes at a coolant-flow ratio of 0.018, a fatigue-type failure occurred in the base region of the strut; the failure was similar to that shown in figure 7. If the fatigue-type failures can be prevented by improved ductility with some sacrifice in stress-rupture properties, a tempering temperature higher than 1375° F will be required.

Strut blades 5 and 6. - Strut blades 5 and 6 were previously used in the limited heat-transfer and cyclic endurance investigation of reference 3. As cited in the reference, the blades successfully completed 10 cycles at each coolant-flow ratio of 0.05 and 0.03. These blades were also used in the heat-transfer investigation described herein. This cyclic endurance investigation is a continuation of the endurance investigation of reference 3 and was conducted at lower coolant-flow rates.

Cyclic-type operation was chosen so that the blades would be exposed to rapid changes in gas temperature and centrifugal stress level. Rapid changes in gas temperature cause severe temperature gradients and resulting thermal stresses between the shell and the strut, a result of the quicker temperature response of the thin shell to this change as compared with the slower response of the more massive strut. During the course of the cyclic endurance investigation, strut and gas temperature measurements were made in the acceleration and deceleration phases of the cycles. The response of strut temperatures was measured to obtain an insight into the severity of the resulting thermal stresses. Temperatures at the leading-edge, midchord, and trailing-edge regions of the strut are shown in figure 10 for a range of coolant-flow ratios. Considerable time lag of the strut temperatures was observed for the coolant-flow rates investigated. In many instances, a period of 5 minutes or longer elapsed before the temperature of the strut reached equilibrium. Shell temperatures were not measured because of the aforementioned reasons. The large time lag of the strut in conjunction with the quick response (or small time lag) that would be expected for the thin shell is the cause of the severe thermal stresses.

In this investigation, the two blades successfully completed 10 additional cycles at a coolant-flow ratio of 0.02. The two blades did not fail at these coolant-flow rates, even when operated with extensive cracks in the fillet between the shell and the blade base. These cracks, which occurred prior to the heat-transfer and cyclic tests of reference 3, were the result of an attempt to weld the shell to the blade base at several locations where incomplete brazing was observed.

On the first cycle at a coolant-flow ratio of 0.01, blade 6 failed in fatigue in the base region of the strut; the failure being similar to those described previously. At the time of the heat-transfer investigation it was expedient in the test program to omit the usual heat treatment, and as a result blade 6 was tested in the "as brazed" condition (heat treatment D). This condition results in a brittle material which

in combination with braze penetration may account for the relatively early blade failure. The total operating time for this blade was 18 hours and 37 minutes, which included operation in the heat-transfer investigation. In the heat-transfer investigation, the blade was operated at higher coolant-flow ratios and lower engine speeds than blades of the endurance investigation.

Cyclic operation was continued on blade 5 at the coolant-flow ratio of 0.01. On the first cycle the tests were interrupted because of a failure of the shell in the leading-edge region, where a 1/2-inch-diameter hole developed at 1/4 span. (This blade shell was damaged previously at this location while the blade was being removed from the test engine.) A patch of 0.007-inch sheet was then brazed across the hole and the cyclic operation on this blade was continued. After 14 successful cycles at the coolant-flow ratio of 0.01, a failure of the patch caused the termination of tests on this blade. Upon removal of the blade shell from the strut, a microscopic examination of the strut fins in the shell fillet region on the suction surface of the blade revealed fatigue cracks in the fins which had already progressed toward the center of the strut. The total operating time of blade 5 at a coolant-flow ratio of 0.01 and rated speed of 11,500 rpm was approximately $3\frac{3}{4}$ hours. This time is comparable with that of blades 1 and 3 operated at the same coolant-flow ratio. The entire operating life of blade 5 was 25 hours and 7 minutes and included operation during the cyclic and heat-transfer phase of this investigation and that of reference 3. The relatively long life of this blade, which was subjected to four braze cycles, is believed to be attributable to the use of rapid brazing cycles, as will be discussed in the subsequent section.

The results obtained in the cyclic phase of the investigation were less than a goal of 200 cycles, which according to reference 8 was considered a sufficient length of time to demonstrate adequate blade durability. These results were encouraging, however, because totals of 44 cycles and 30 cycles were successfully completed on blades 5 and 6, respectively. The results indicated that no additional problems were encountered during cyclic operation other than the fatigue failures experienced earlier in the steady-speed engine operation of blades 1 through 4.

Summary of strut blade-durability investigation. - A summary of the strut blade life, corresponding heat treatments, and other pertinent operating information for the six strut blades is given in table III. A considerable amount of design information was obtained from the endurance testing of the six strut blades. It was found that braze penetration was a more serious problem than expected and should be given due consideration in the design of strut-type blades. It is also advisable to fabricate the blade in as few braze cycles as possible as well as to reduce the amount of brazing in order to minimize braze diffusion. Braze diffusion can probably be reduced by the use of faster brazing cycles than those used herein.

During each braze cycle, blades 1 to 4 were subjected to a temperature of 2150° F for 15 minutes and temperatures above 1850° F for approximately 2 hours. During this period considerable diffusion can occur. This relatively long duration above 1850° F was required because of the limitation of the heating capacity of the furnace that was used. Blades 5 and 6 were both brazed in a hydrogen furnace. The duration of each braze cycle at elevated temperatures for these two blades was much less than the 2 hours required for blades 1 to 4. A metallurgical examination of blade 6 after failure showed that the braze penetration was less than that for blades 1 to 4, inclusive. An examination of blade 5 was not made, although the braze penetration should compare with that for blade 6. It is believed that the favorable life of blade 5, as compared with blades 1 and 3 which were operated at the same coolant-flow ratio of 0.01, is caused by this reduced braze penetration. Diffusion of the braze into the strut material can probably be further reduced by the use of a more rapid cycle obtained from an induction heating element located inside the furnace. Another possible means of eliminating the braze diffusion problem in the base region of the strut is to cast the strut integrally with the blade base and thereby eliminate the brazing cycle that is normally required for this operation.

In the design of strut-type blades, effort should also be made to reduce the notch effect in the fillet region of the blade; the notches in conjunction with a nonductile type of material are thought to be the primary cause of the blade failures reported herein. Generous fillets and a tempering temperature resulting in good ductility should be used when possible.

A valid comparison of strut blade life with that of the 10-tube, shell supported blade of reference 6 could not be made with any degree of certainty because of the limited strut blade durability data. The limited number of strut blades tested (six), however, did give indications that this type of blade will probably have a greater life than that of the tube-filled, shell-supported blade over the range of coolant-flow ratios investigated.

SUMMARY OF RESULTS

The following results were obtained as part of a development program conducted to determine the cooling effectiveness and durability of air-cooled, strut-supported turbine blades. The strut blades used in this investigation had an airfoil shape, twisted from base to tip. The struts for these blades were machined from 17-22A(S) steel.

1. Appreciable cooling of the support member of the strut-supported blade was obtained during operation in a full-scale turbojet engine. At a coolant-flow ratio of 0.012 and a turbine-inlet gas temperature of

1815° F, for example, the difference between the average strut temperature of 1025° F and the effective gas temperature was approximately 575° F. At this gas temperature the differences between the midchord strut temperature and the leading-edge regions and between the midchord and the trailing-edge regions were 20° and 175° F, respectively; these values agreed well with those obtained at a lower inlet gas temperature of 1650° F.

2. Calculated midchord strut temperatures at the 3/8-span location were in favorable agreement, as expected, with strut temperatures measured during engine operation at a turbine-inlet temperature of 1815° F. Calculated midchord strut temperatures were approximately 20° F lower than experimental values.

3. Calculated spanwise blade temperatures for a turbine-inlet gas temperature of 1815° F verified the need of a protective coating of the steel strut to prevent oxidation. Calculated shell temperatures indicated that a protective coating was not needed for the shell of N-155 material.

4. The results of the steady-speed endurance investigation of four strut-supported blades, conducted in a full-scale turbojet engine at a speed of 11,500 rpm and turbine-inlet temperature of 1670° F, gave indication that strut blade life will probably be greater than that for a 10-tube, air-cooled, shell-supported blade made from the same material and operated at similar coolant-flow ratios. The four blades failed in fatigue at the base region of the strut and not in stress-rupture as desired from the blade life viewpoint. Calculated centrifugal stress in the strut at this point was 44,000 pounds per square inch. A metallurgical examination of the blades after failure showed severe braze penetration into the strut material. Blade failures were attributed to the combination of braze penetration and a strut material having insufficient ductility to withstand the combination of the imposed vibratory and centrifugal stresses and the stress concentrations caused by the notches in the fillet region of the blade. Elimination of the fatigue failures to increase blade life would probably require a different fabrication technique and heat treatment.

5. Two strut blades were subjected to a cyclic endurance investigation in a full-scale turbojet engine. These cycles consisted of a rapid acceleration from engine idle to rated engine conditions, followed after 15 minutes at rated conditions by a rapid deceleration to idle conditions. In addition to the successful completion of 10 such cycles at coolant-flow ratios of 0.05 and 0.03 as reported earlier, both blades successfully completed 10 additional cycles at 0.02. One of the two blades successfully completed 14 cycles at 0.01. Blade failures also occurred in

fatigue in the base regions of the struts. The cyclic endurance results were encouraging even though the average life of each blade (approximately 40 cycles) was less than a goal of 200 cycles.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 25, 1954

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TABLE I. - SUMMARY OF HEAT-TRANSFER INVESTIGATION

Engine speed, rpm	Average effective gas temperature (uncooled blade temperature), °F	Turbine inlet gas temperature, °F	Coolant-flow ratio	Strut temperature at 3/8 span			Coolant temperature at blade base, °F
				Leading edge, °F	Midchord, °F	Trailing edge, °F	
4,000	1064	1070	0.075	350	345	470	120
			.063	385	380	510	120
			.049	440	440	560	130
			.039	490	490	605	135
			.027	525	520	635	140
			.018	560	560	660	145
			.010	620	615	710	155
8,000	980	1050	0.074	290	280	385	125
			.059	325	315	430	125
			.043	365	355	475	130
			.032	415	405	525	135
			.025	450	440	555	145
			.018	495	485	590	155
			.010	565	550	640	170
10,000	1050	1180	0.072	315	300	415	135
			.056	345	335	460	135
			.041	390	385	520	140
			.030	455	450	580	145
			.025	495	490	620	155
			.017	560	550	665	170
			.009	715	680	740	185
11,500	1425	1650	0.079	420	405	565	160
			.060	470	450	630	165
			.045	525	510	695	175
			.031	620	605	795	185
			.027	670	660	850	195
			.019	755	735	910	215
			.010	1000	960	1040	245
11,500	1590	1815	0.084	460	440	630	170
			.064	510	495	710	175
			.048	585	565	790	180
			.035	680	670	900	195
			.029	740	730	955	210
			.021	820	800	1020	235
			.012	980	955	1130	280

TABLE II. - SUMMARY OF HEAT TREATMENTS

Heat treatment	Process
A	Normalized at 1725° F for 1 hr and tempered at 1225° F for 4 hr. Both operations performed in an argon atmosphere.
B	Normalized at 1725° F for 1 hr and tempered at 1225° F for 4 hr and at 1350° F for 1 hr. All operations performed in an argon atmosphere.
C	Normalized at 1725° F for 1 hr, tempered at 1225° F for 4 hr. Both operations performed in an argon atmosphere. Salt-dipped at 1375° F for 1 hr.
D	As brazed (15 min at 2150° F in vacuum).

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CN-3 back

TABLE III. - SUMMARY OF HEAT-TRANSFER AND ENDURANCE CHARACTERISTICS
OF STRUT-SUPPORTED BLADE

Blade	Phase of investigation	Heat treatment (see table II)	Number of braze cycles	Total running time		Remarks
				Hr	Min	
1	Steady-speed endurance	A	4	2	39	Strut failure after 2 hr 29 min at 0.01 coolant-flow ratio
2	Steady-speed endurance	B	3	33	47	Strut failure after 30 hr 50 min at 0.015 coolant-flow ratio
3	Steady-speed endurance	A	1	3	16	Strut failure after 3 hr 5 min at 0.01 coolant-flow ratio
4	Steady-speed endurance	C	1	17	35	Strut failure after 14 hr 25 min at 0.018 coolant-flow ratio
5	Heat-transfer and cyclic endurance	A	4	25	7	Completed heat-transfer tests and 10 cycles each at 0.05, 0.03, 0.02, and 14 cycles at 0.01 coolant-flow ratio. Test terminated after second failure of shell; previously damaged and repaired during heat-transfer testing
6	Heat-transfer and cyclic endurance	D	4	18	37	Completed heat-transfer tests and 10 cycles each at 0.05, 0.03, and 0.02 coolant-flow ratio. Strut failure on first cycle at 0.01 coolant-flow ratio

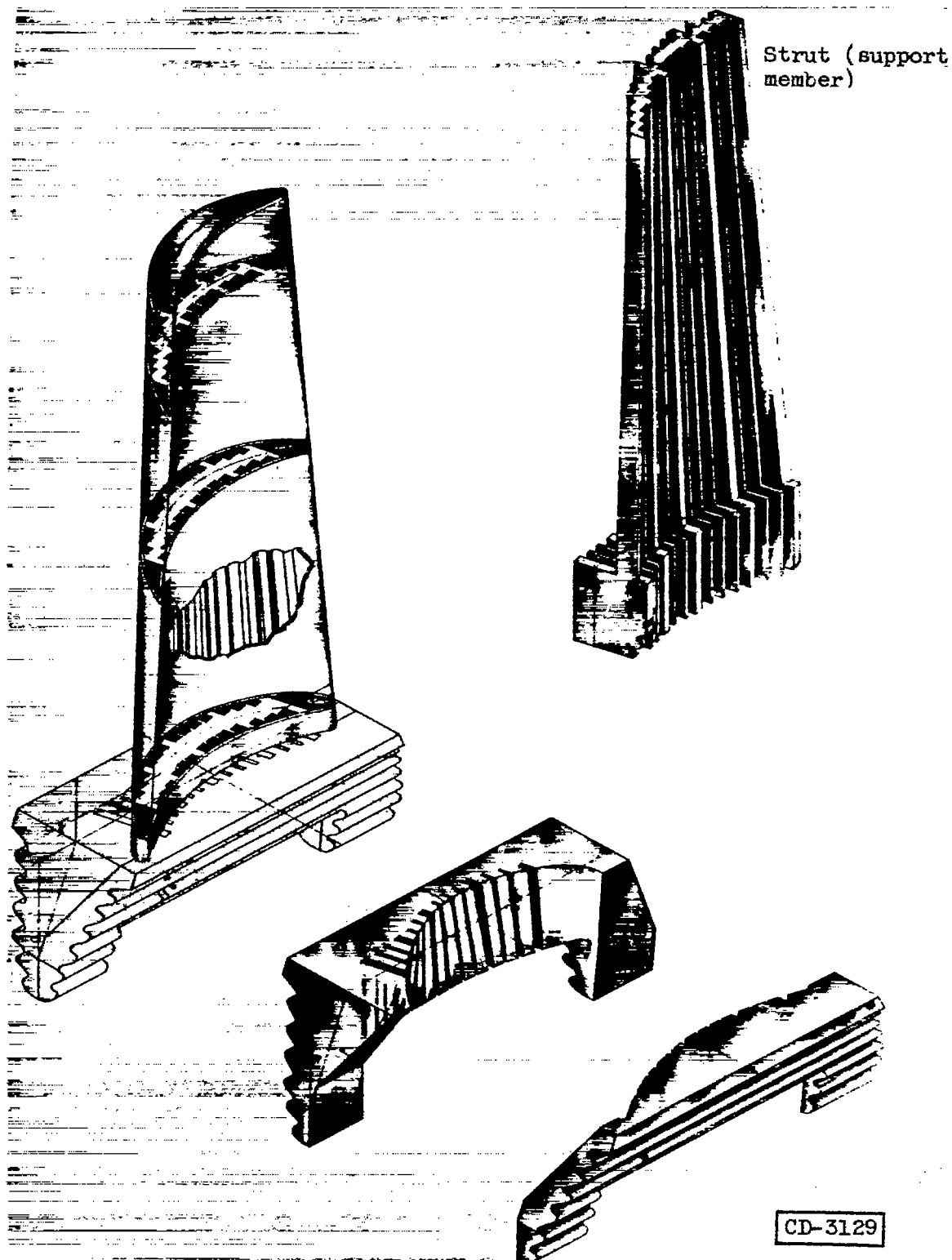


Figure 1. - Isometric view of twisted-airfoil, air-cooled, strut-supported, turbine blade.

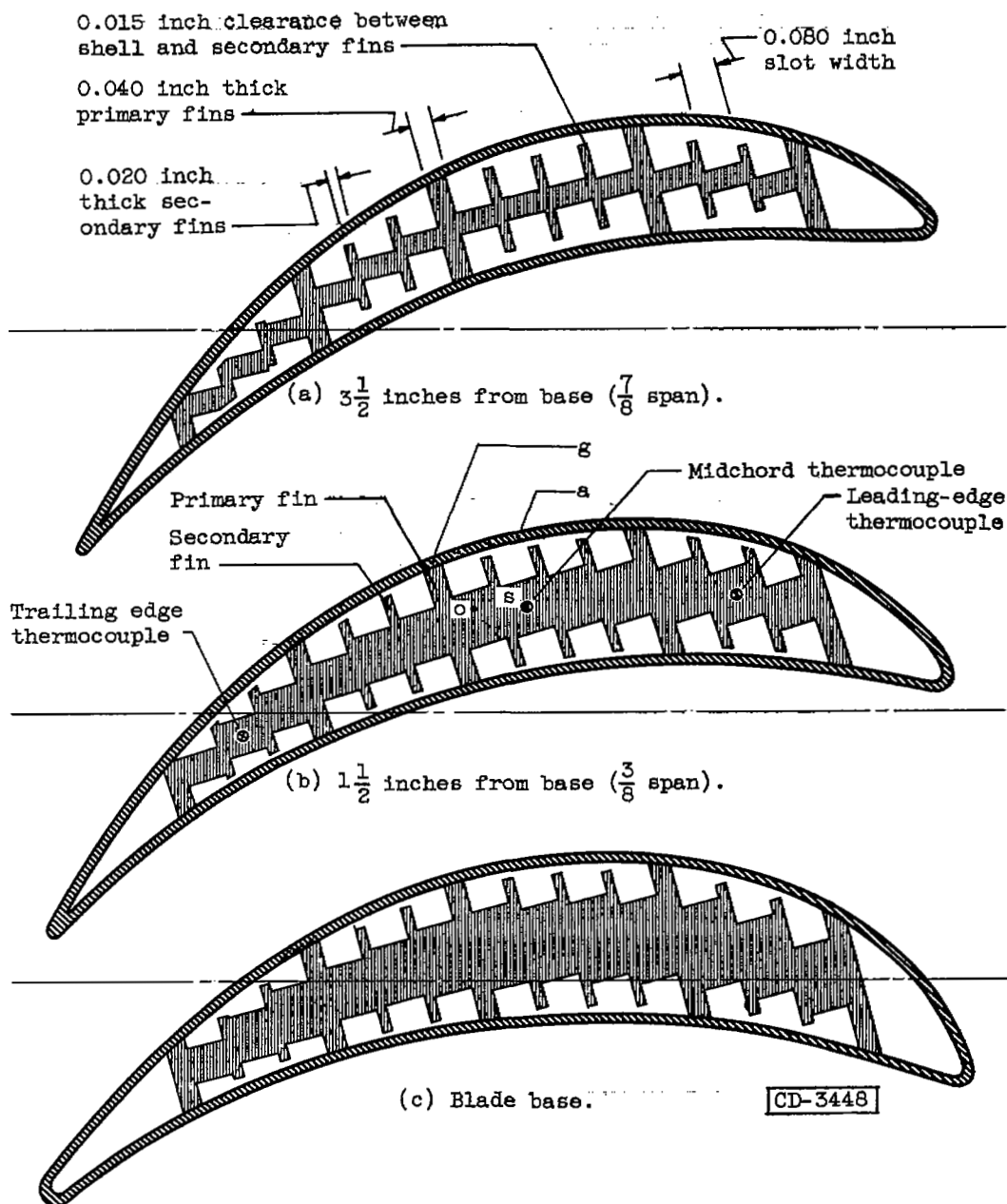
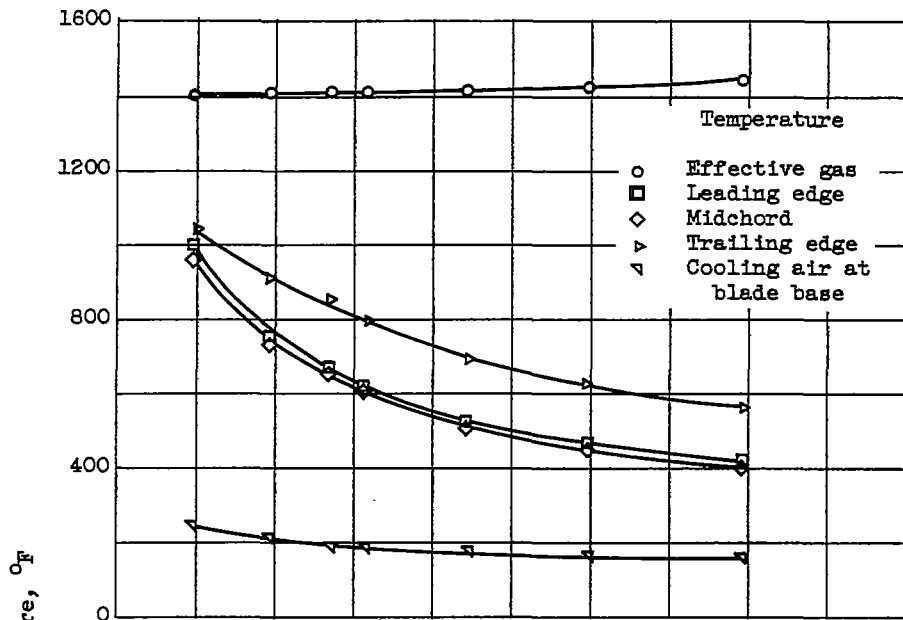
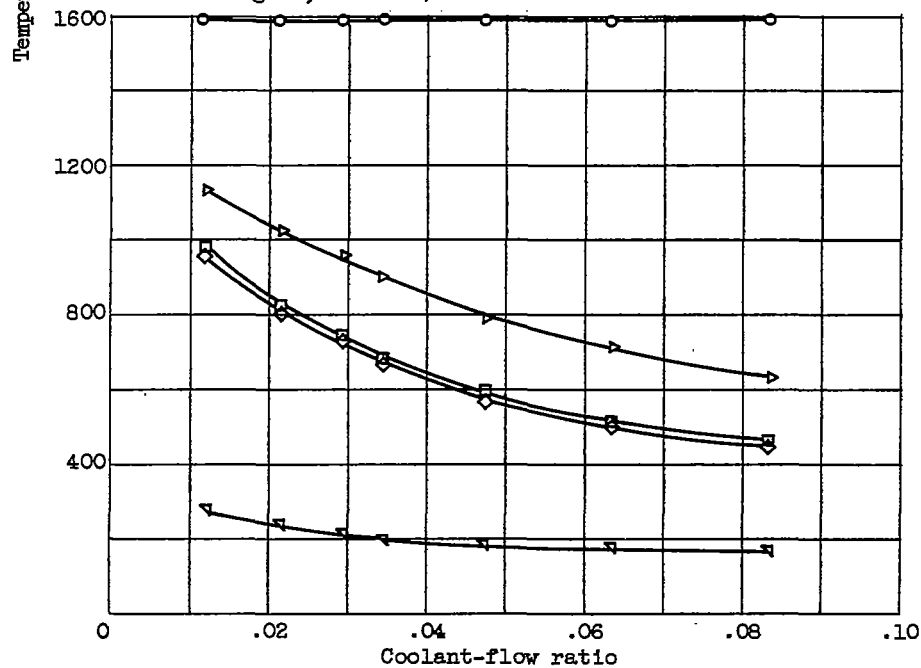


Figure 2. - Profiles of twisted-airfoil, strut-supported blade at three spanwise positions showing pertinent blade dimensions and locations of thermocouples and points for temperature analysis.



(a) 1650° F nominal turbine-inlet gas temperature. (Data from fig. 6, ref. 3.)



(b) 1815° F nominal turbine-inlet gas temperature.

Figure 3. - Variation of experimental strut temperatures of air-cooled, strut-supported blade at 3/8 span with coolant-flow ratio at 11,500 rpm for nominal turbine-inlet gas temperatures of 1650° and 1815° F. (Measured effective gas temperature and cooling-air temperature at blade base are also shown.)

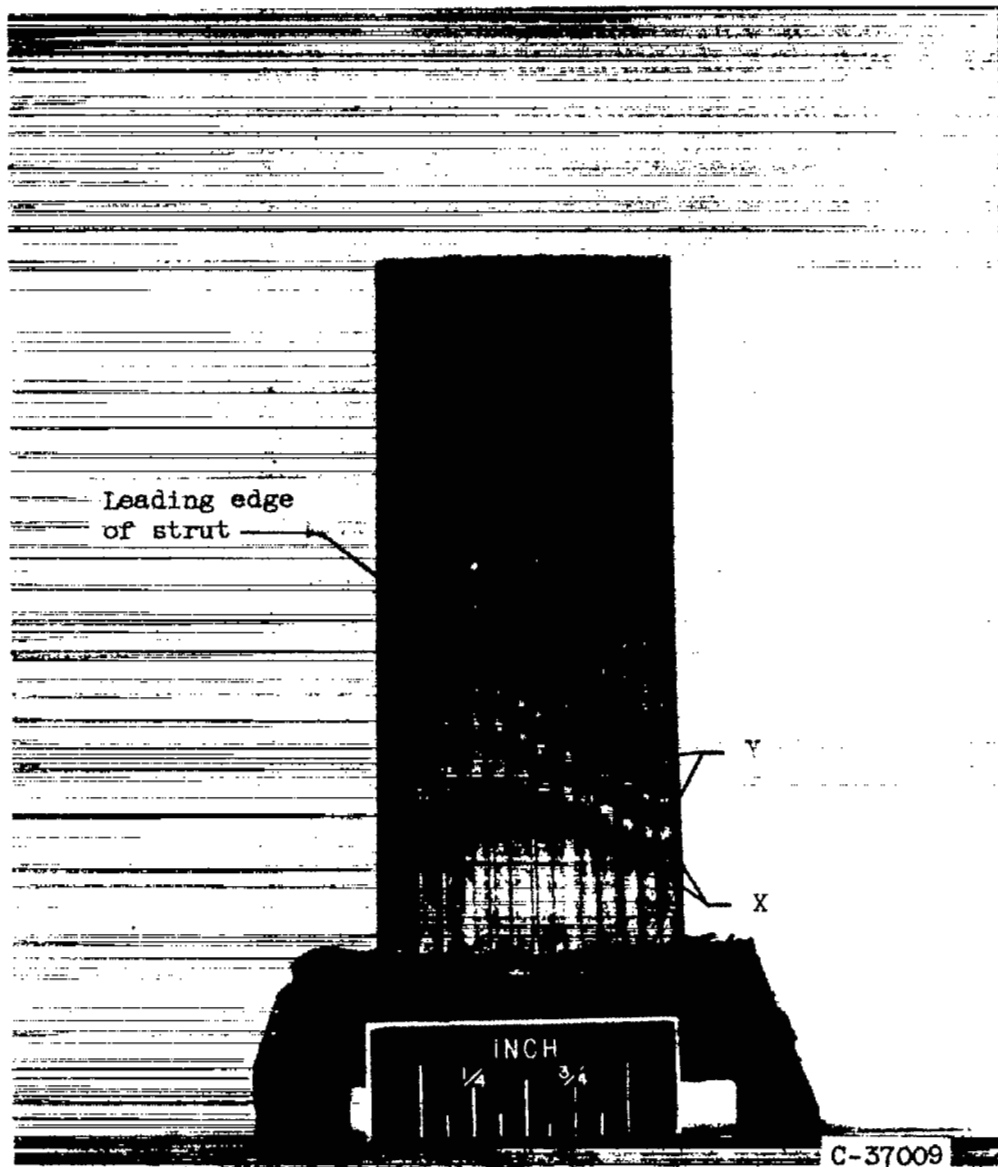


Figure 4. - Constant temperature lines (temper color bands) of strut-supported blade after heat-transfer tests.

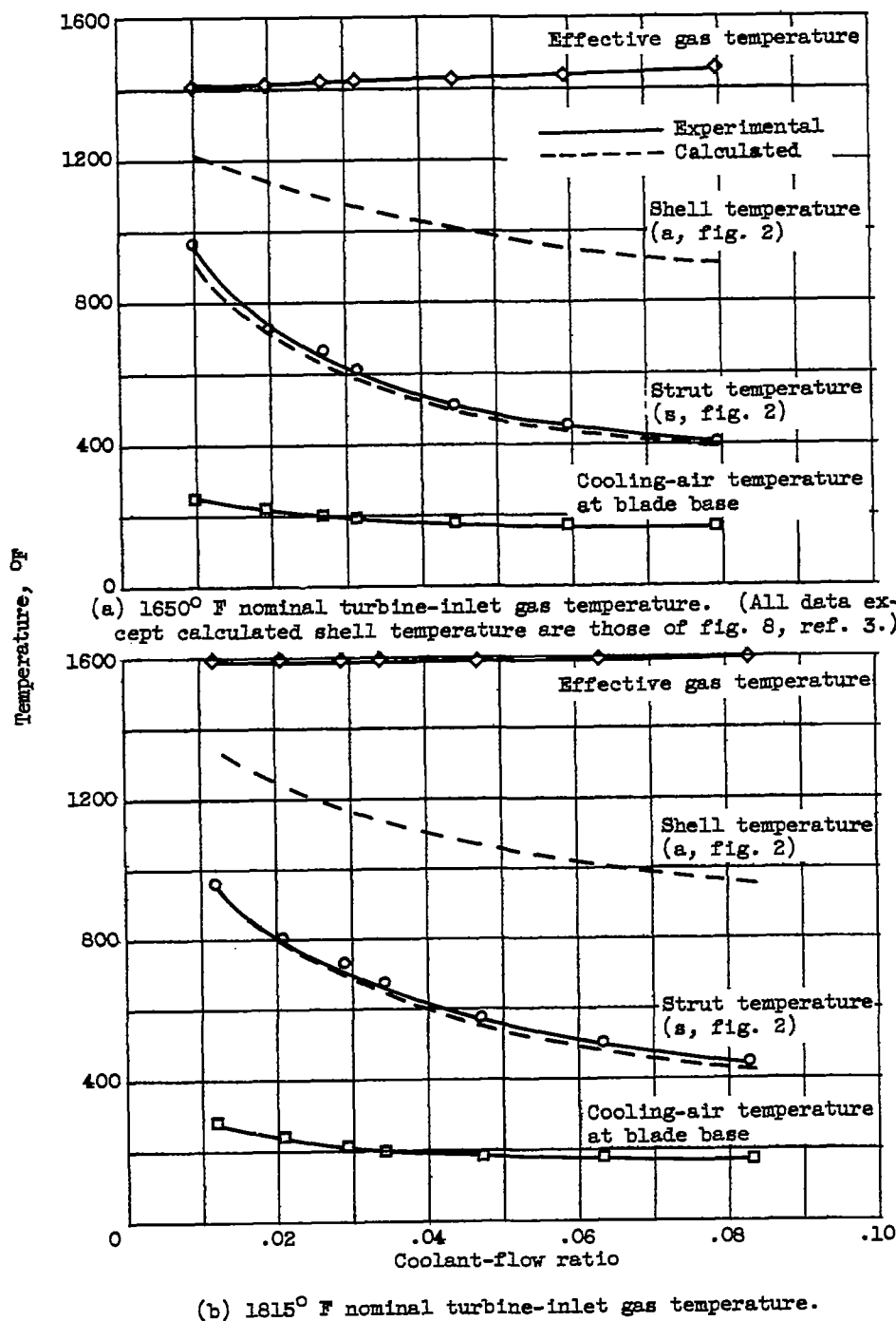


Figure 5. - Comparison of calculated and experimental midchord strut and shell temperatures at 3/8 span for range of coolant-flow ratios. Comparison made for nominal turbine-inlet gas temperatures of 1650° F and 1815° F for engine speed of 11,500 rpm. Cooling-air temperature at blade base also shown.

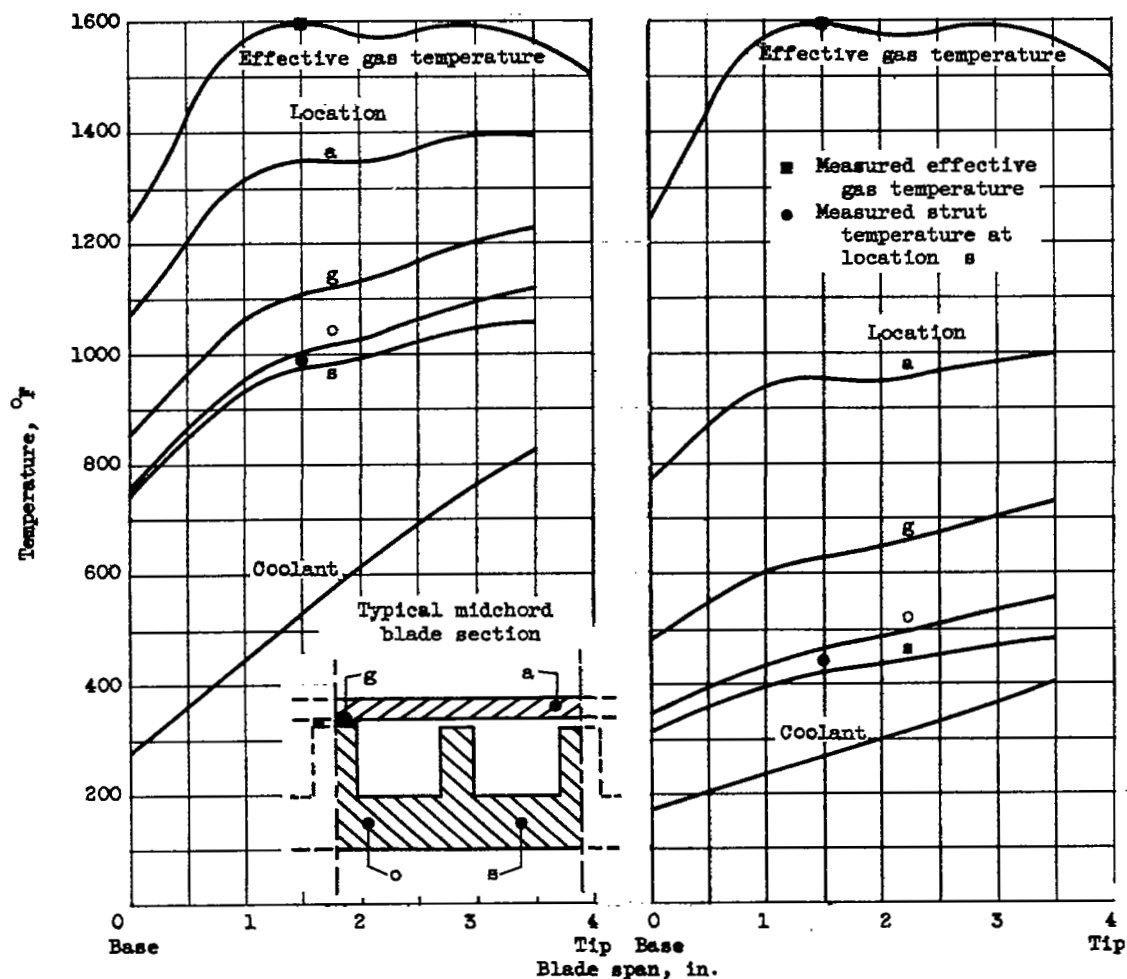
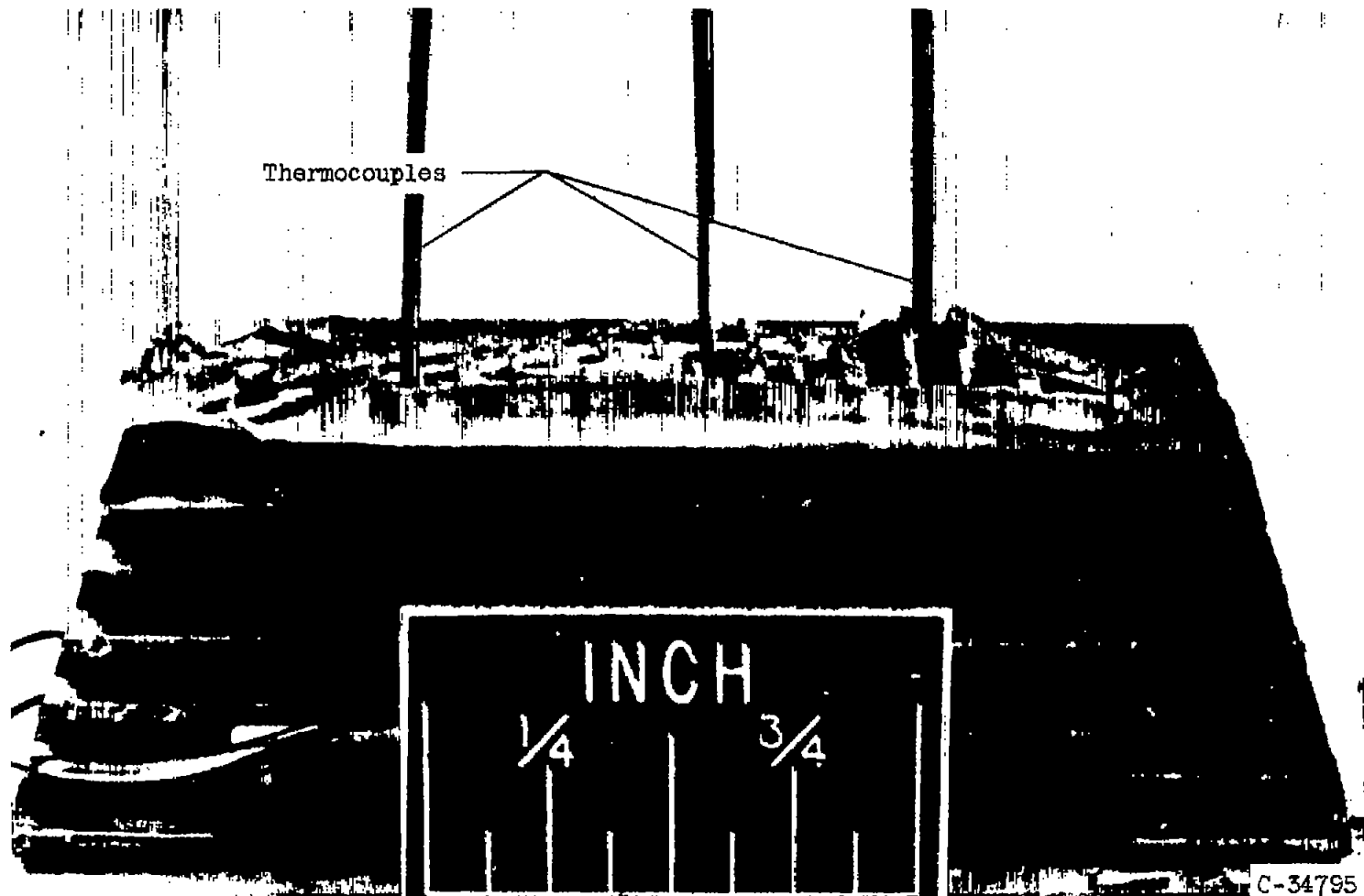
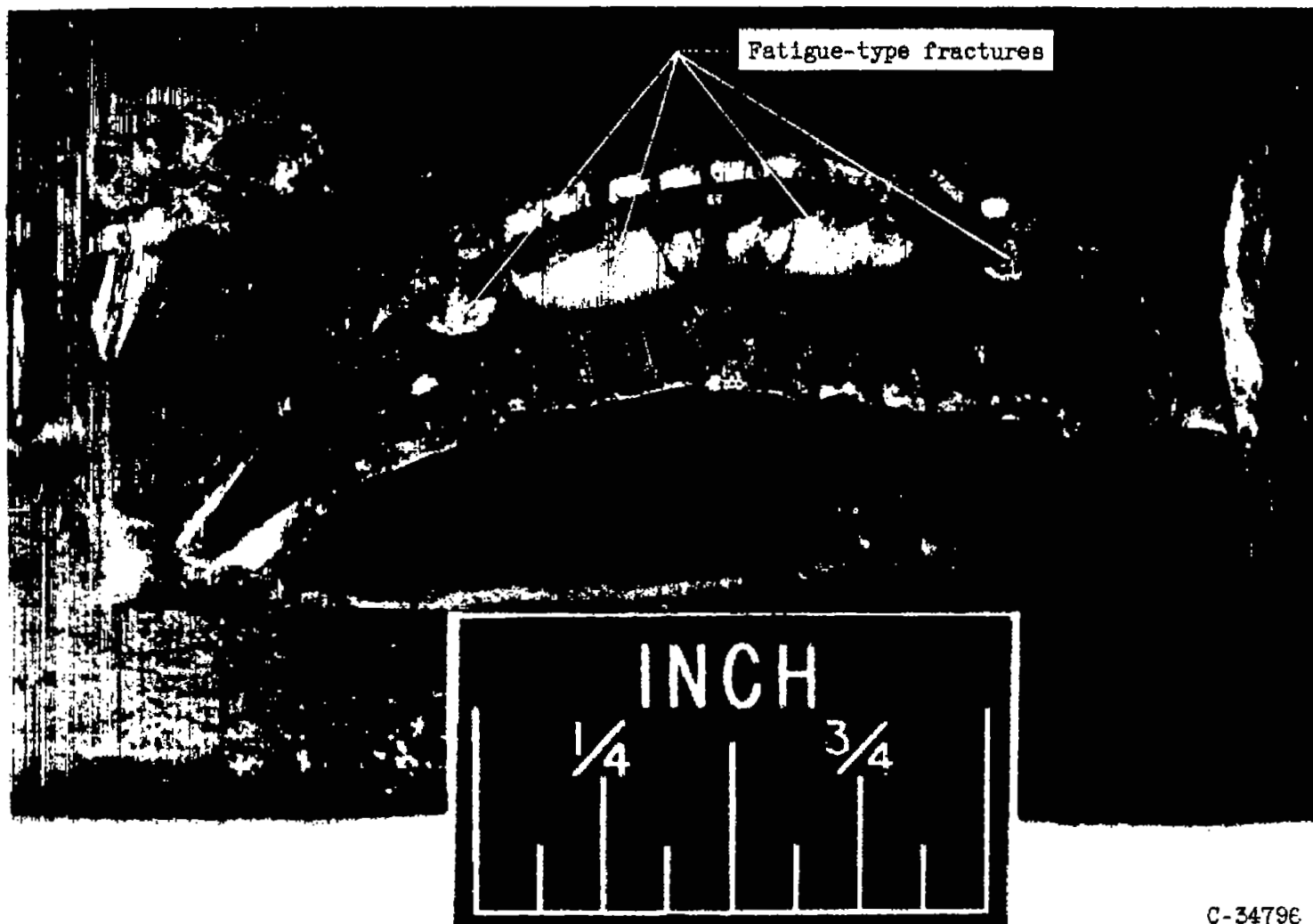


Figure 6. - Calculated spanwise temperature distribution for several midchord blade locations for 0.012 and 0.084 coolant-flow ratios at nominal turbine-inlet gas temperature of 1815° F. Measured strut and effective gas temperatures at $\frac{3}{8}$ span ($1\frac{1}{2}$ in. from base) also shown.



(a) Side view.

Figure 7. - Failure of strut blade 1.



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(b) Top view.

Figure 7. - Concluded. Failure of strut blade 1.

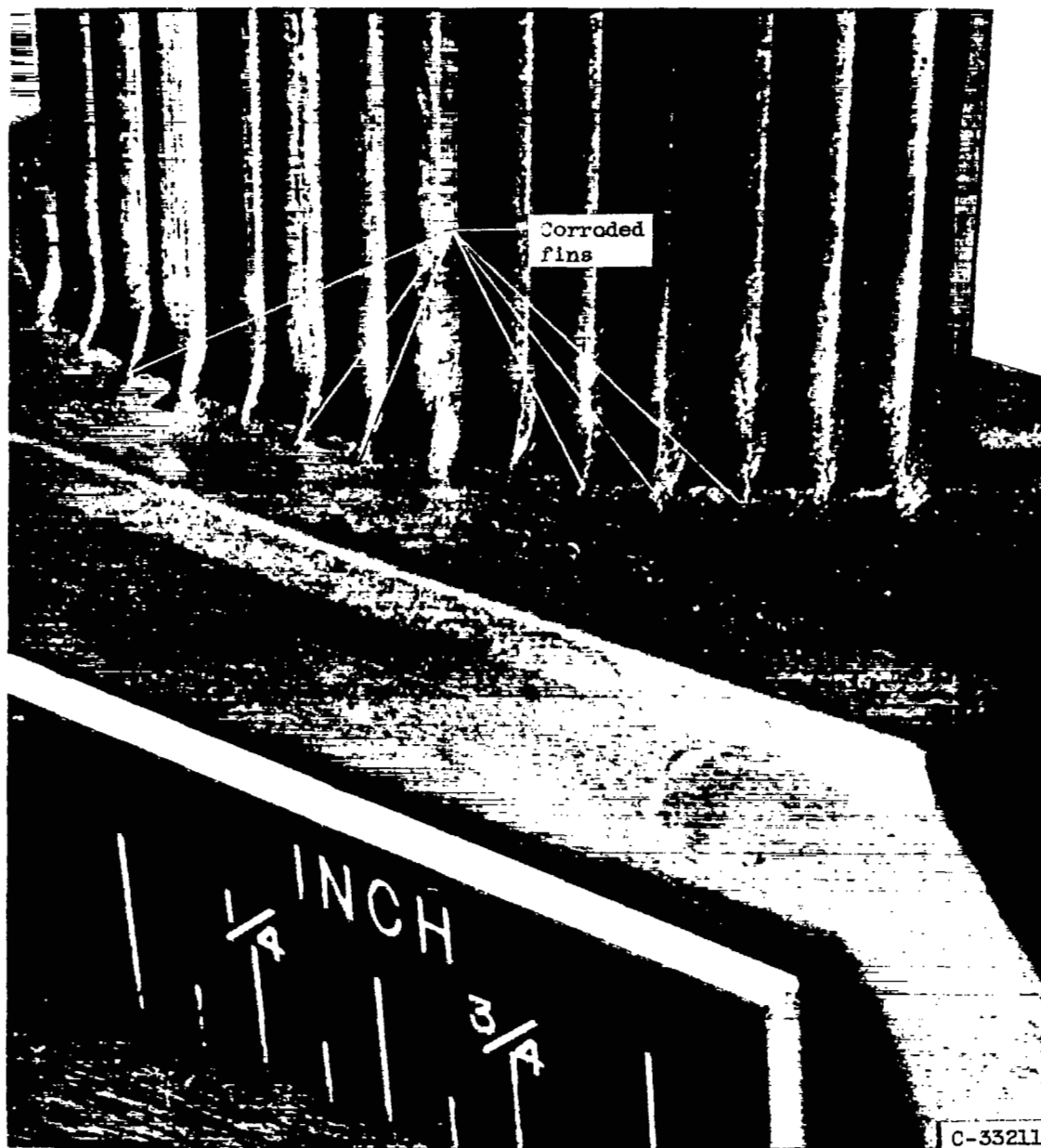


Figure 8. - Corrosion of fins in fillet region of strut blade.

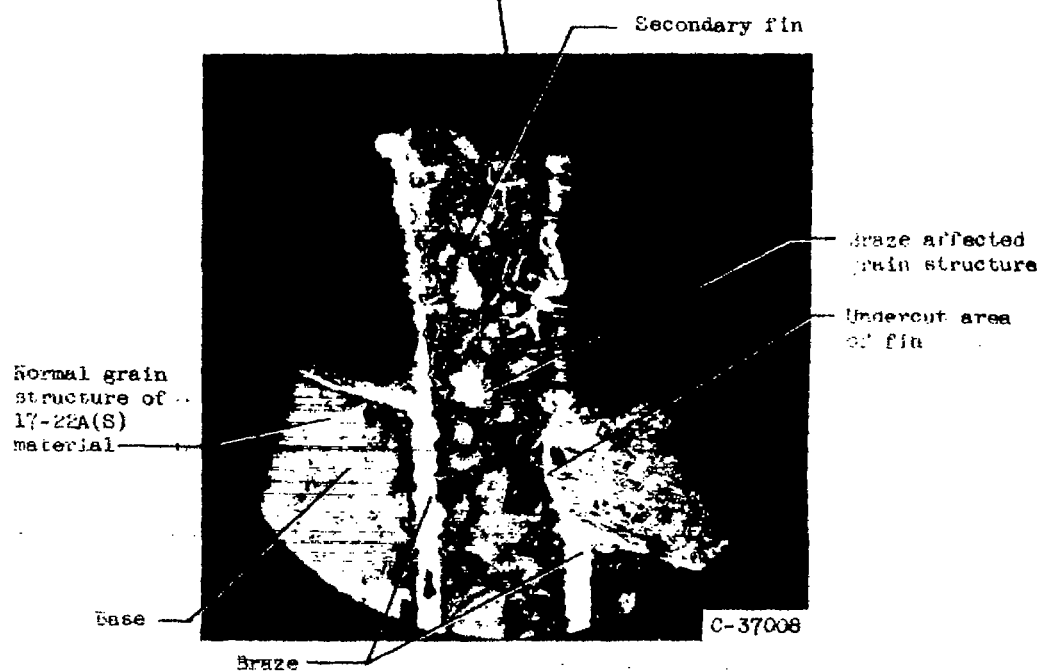


Figure 9. - Microstructure (40X size) of section of strut fin and blade base showing extent of braze penetration for strut blade 2.

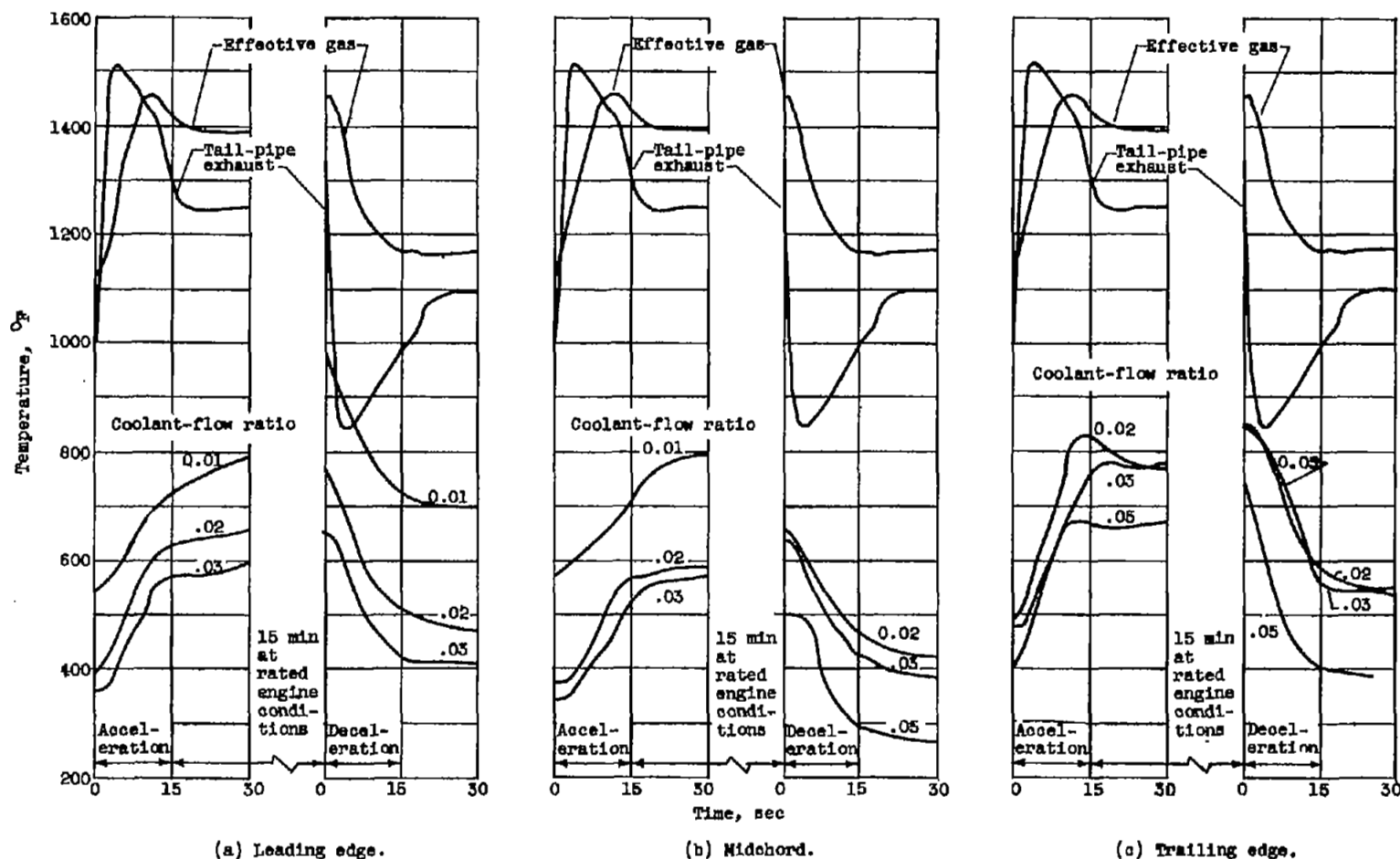


Figure 10. - Variation of effective gas, tail-pipe exhaust, and strut temperatures experimentally obtained during cyclic endurance investigations. Values of leading-edge, midchord, and trailing-edge strut temperatures shown for several coolant-flow ratios.